Long-term Global Morphology of Gravity Wave Activity Using UARS Data

Contract NAS5-98045

Quarterly Report

Dec 18, 1999 – Mar 18, 2000

Principal Investigator

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ABSTRACT

Gravity waves in satellite data from CRISTA and MLS are studied in depth this quarter. Results this quarter are somewhat limited due to the PI's heavy involvement throughout this reporting period in on-site forecasting of mountain wave-induced turbulence for the NASA's ER-2 research aircraft at Kiruna, Sweden during the SAGE III Ozone Loss and Validation Experiment (SOLVE). Results reported concentrate on further mesoscale modeling studies of mountain waves over the southern Andes, evident in CRISTA and MLS data. Two-dimensional mesoscale model simulations are extended through generalization of model equations to include both rotation and a first-order turbulence closure scheme. Results of three experiments are analyzed in depth and submitted for publication. We also commence simulations with a three-dimensional mesoscale model (MM5) and present preliminary results for the CRISTA 1 period near southern South America. Combination of ground-based temperature data at 87 km from two sites with global HRDI data was continued this quarter, showing stationary planetary wave structures. This work was also submitted for publication.

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1. Work and Results this Quarter

1.1 Two-Dimensional Mesoscale Model Simulations of Stratospheric Mountain Waves over the Southern Andes

Last quarter we reported on a sequence of "real world" simulations of flow across the southern Andes using a two-dimensional nonlinear nonhydrostatic mesoscale model that we have developed.

This quarter we adapted the model further and conducted a series of more involved simulations. An impediment to the first series of simulations, reported in earlier quarters, was that wave breaking in the stratosphere led rapidly to numerical instabilities that forced the simulations to be terminated after ~12 hours. To alleviate this, we extended the model equations to include a first-order turbulence closure scheme [*Lilly*, 1962], which acts to mix breaking regions in the flow. We also included rotation in the equations, necessitating inclusion of meridional wind terms and an additional equation for meridional momentum balance. To ensure the new model algorithms operated satisfactorily, we first used the new version of the model to accurately reproduce mountain wave patterns from previous two-dimensional model experiments [*Doyle et al.*, 2000].

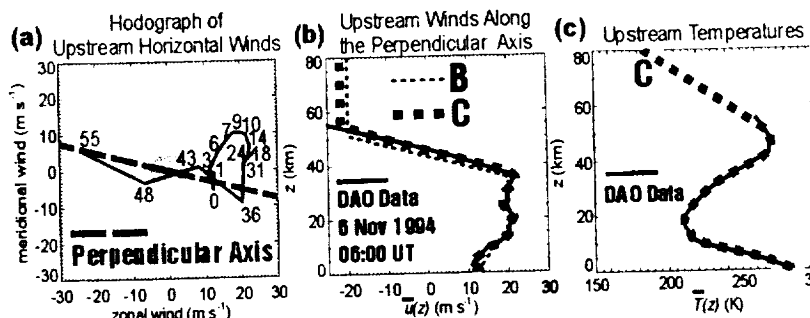

Figure 1: (a) hodograph of horizontal winds upstream of the Andes from DAO assimilated data on 6th. November, 1994 at 06:00 UT. The altitudes (in kilometers) of each wind value are labeled along the hodograph trace. Orientation of the model experiment axis is shown with broken curve; (b) black solid curve shows upstream DAO wind profile along the perpendicular axis. Other labeled curves show model wind profiles used in Experiments A, B and C using the mesoscale model; (c) vertical profile of upstream DAO temperatures (solid black curve), and the model curves used in Experiments A, B and C.

From there, we formulated and performed three experiments, labeled A, B and C, which used wind and temperature profiles as shown in Figure 1. Experiment A used an idealized wind profile that omitted the westward shear layer in the DAO profile above 35 km (Figure 1b). This control experiment allowed us to study mountain wave generation and propagation to stratosphere-mesosphere levels above the Andes without the complication of critical-level effects, and also allowed us to tune the sponge layer. In Experiment B, a linear westward shear layer was introduced above 35 km, yielding a critical level (zero mean wind line) at z ~43 km. Experiment B allowed us to introduce the critical layer, while maintaining an identical atmospheric situation to Experiment A below 35 km. To this end, both experiments used background temperatures from the 1976 U.S. Standard Atmosphere at mid-latitudes [*Minzner*, 1977], which fit the upstream DAO temperatures from ~0-55 km quite well (Figure 1c). Experiment C used cubic spline fits to the DAO wind and temperature profiles from 0-55 km. This yielded a zero wind line at z ~46 km, slightly higher than in Experiment B. Lacking any DAO data to fit above 55 km, from 55-80~km we used constant winds (Figure~1b) and a linear temperature gradient equal to that in Experiments A and B (Figure 1c).

In all three experiments, mountain waves entered the upper stratosphere after a few hours and produced overturning isentropes after ~6 hours. Figure 2 plots contours of the total (wave + mean) potential temperature $\Theta(x,z,t)$ after t = 18 hours in each experiment over the orographic region of the Andes. Colors show contours of temperature perturbations $T'(x,z,t)$. We see that the critical levels in Experiments B and C efficiently absorb mountain waves, and yield rapid wave shortening and intense breaking at closely underlying altitudes. Despite the different wind profiles and the significant amounts of overturning (nonlinearity) and mixing by this time, the large-scale wave structures below 35 km look very similar in all three experiments.

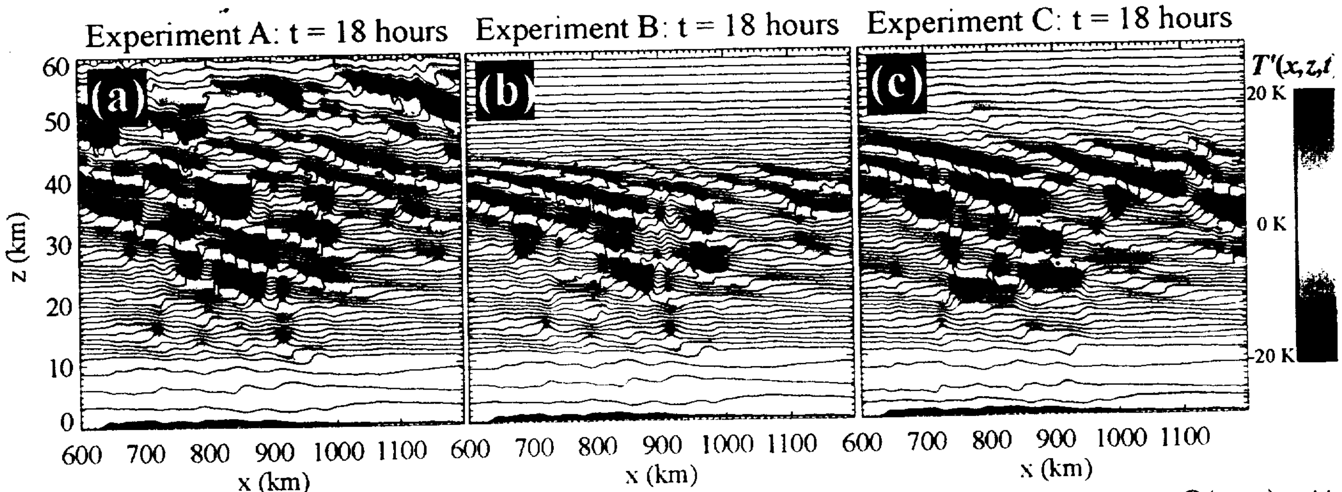

Figure 2: Temperature fields after 18 hours in Experiments A, B and C. Contours show isentropes $\Theta(x,z,t)$, with constant logarithmic separation between adjacent contours. Temperature perturbations $T'(x,z,t)$ are overlayed using the blue-red color scheme shown to the right. Underlying topography is shown in black.

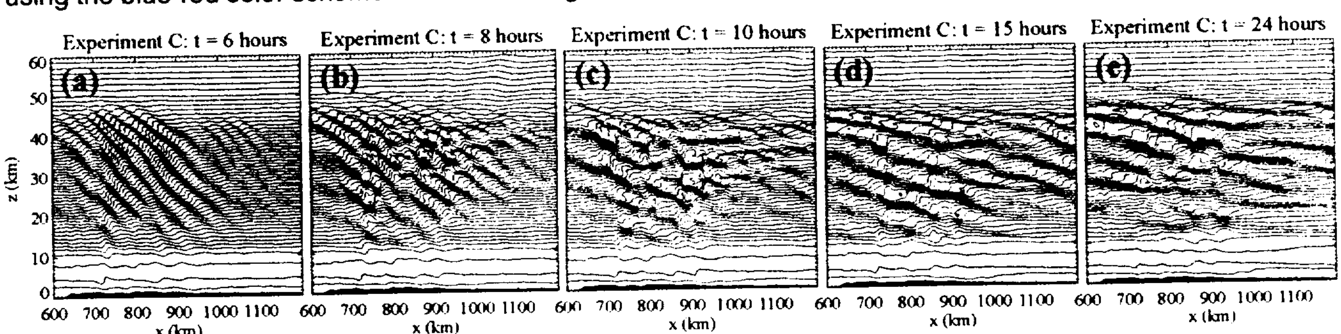

Figure 3: Contours of isentropes $\Theta(x,z,t)$ from Experiment C after t = 6, 8, 10, 15 and 24 hours. Same constant logarithmic separation between contours is used in each panel. Underlying topography is shaded.

The wave fields evolve significantly with time, as illustrated in Figure 3 using results from Experiment C. The middle atmosphere is dominated initially by short horizontal wavelengths, which trigger vigorous overturning and mixing by 8 hours. The turbulent zones persist and seem to move downstream after 10 hours. Thereafter, progressively longer horizontal wavelengths come to dominate the wave field, and less vigorous overturning is evident. After 24 hours, waves at lower stratospheric levels are suppressed compared to their earlier intensities.

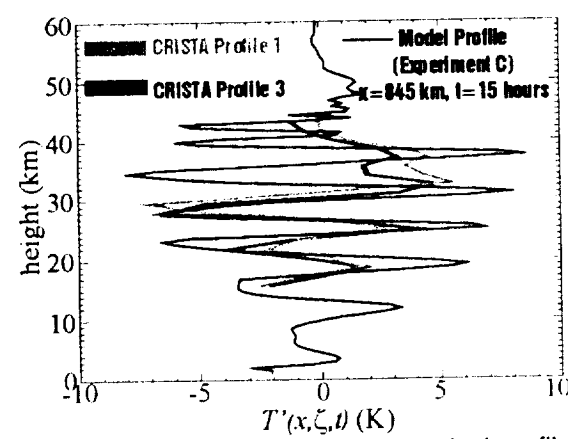

Figure 4: Black curve shows a vertical profile of temperature perturbations at x = 845 km, 15 hours into Experiment C. Two shaded solid curves reproduce the temperature perturbation profiles acquired by CRISTA at locations 1 and 3 in Figure 5 (after *Eckermann and Preusse* [1999].

The wavelength selection and group velocity arguments discussed in previous reports again explain the wavelength selection observed here in Figure 2, as well as the time evolution of dominant horizontal wavelengths evident in Figure 3. These new simulations extending out to 24 hours (due to stability from the new numerical turbulence scheme) show much longer horizontal wavelength waves in the stratosphere than before, consistent with the need for such long wavelength waves to be present in order for the CRISTA and MLS limb scans to resolve them.

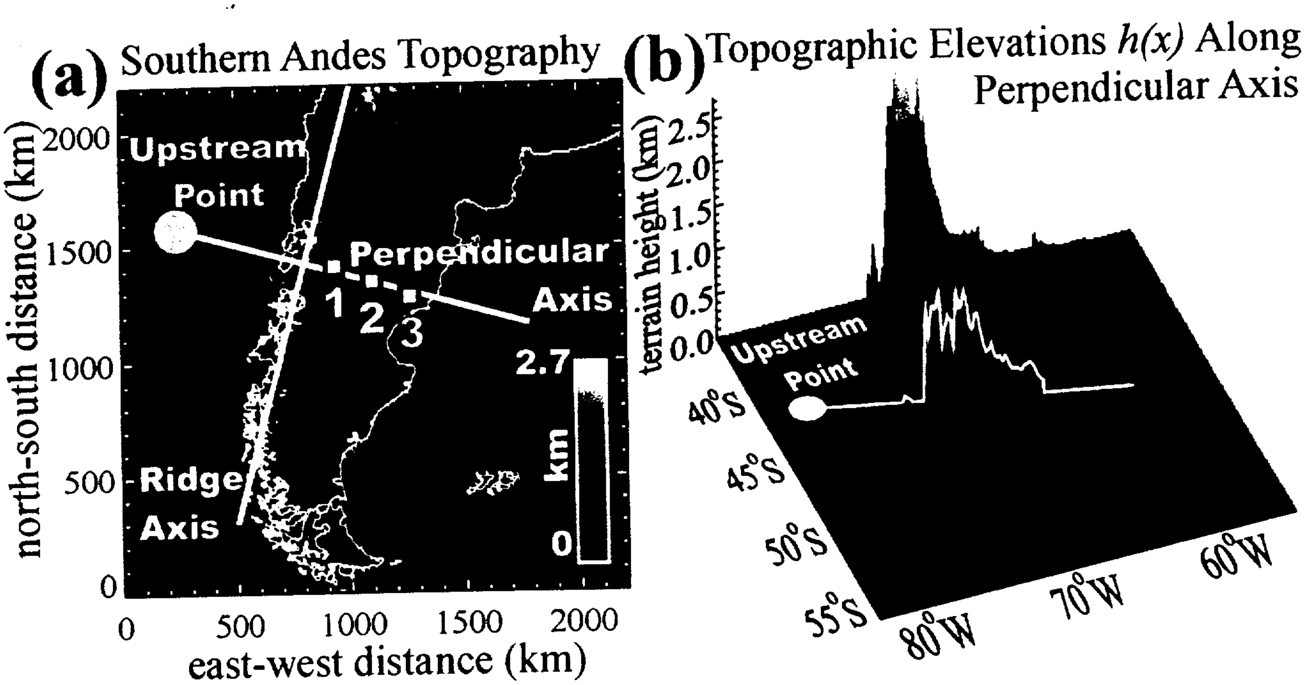

Figure 5: Topographic elevations over southern South America, plotted as (a) filled contours in Cartesian coordinates, (b) three-dimensional elevations in Mercator coordinates. Squares labeled 1,2 and 3 in (a) show locations of temperature profiles acquired by CRISTA. Raw elevations *h(x)* along the perpendicular axis in (a) are plotted in (b). The blue dot in both figures is the upstream point where mean winds and temperatures are computed from DAO data.

The general form of the profiles over the Andes compares favorably with the CRISTA data. Figure 4 plots a sample temperature perturbation profile from Experiment C at x = 845 km, a location between points 1 and 3 over the Andes where CRISTA acquired these profiles, as shown in Figure 5a. The CRISTA profiles at these points are overlaid in Figure 4. The wavelength, amplitude and general height variation of the model profile are all quite similar to the data. Oscillations in Experiment C seem to penetrate slightly higher prior to shortening and dissipating below the critical layer. Note too that the amplitudes of the CRISTA profiles are probably underestimated due to instrumental effects, and that CRISTA cannot resolve any waves of vertical wavelength less than ~3-5 km [*Eckermann and Preusse*, 1999].

Thus these enhanced two-dimensional mesoscale model simulations with turbulent diffusion and rotation have produced results that compare well with the observations. During this quarter these results were written up, submitted and then accepted for publication after peer-review and revision [*Tan and Eckermann*, 2000].

1.2 Three-Dimensional Mesoscale Model Simulations of Stratospheric Mountain Waves over the Southern Andes using MM5

This quarter we initiated an entirely new modeling aspect of the project, in collaboration with Dr. Andreas Dörnbrack of the Deutsche Institut für Luft und Raumfahrt (DLR) in Oberpfaffenhofen, Germany. Our mesoscale model simulations to date have used a two-dimensional model, whereas many features of the topography and winds over the southern Andes are intrinsically three-dimensional, as evident from Figure 1a and Figure 5.

During this quarter the PI spent much time in Kiruna performing stratospheric mountain wave forecasts for the NASA SOLVE mission. Also in the field was Dr. Andreas Dörnbrack who was running a stripped-down version of the Penn State Mesoscale Model 5 (MM5) to provide forecasts of large-scale mountain waves in the stratosphere over northern Scandinavia [e.g., *Dörnbrack et al.*, 1999]. Given the

MM5 model's ability to simulate the largest scale mountain waves, which CRISTA and MLS measure, then we began discussions about performing MM5 simulations over southern Scandinavia during the CRISTA 1 mission period to see if this model could cast light on the three-dimensional nature of mountain waves radiated into the stratosphere from this region.

Results from a test run are shown in Figure 6. The MM5 model was initialized using archived analysis ECMWF data for 5th. November, 1994 at 0:00 Z, and then was integrated for 36 hours thereafter in dry mode with an upper level of ~28 km and a horizontal grid resolution of ~27 km. Figure 6a shows the regional domain used for this run, with Andean topographic elevations contoured.

The red curve in Figure 6a shows a horizontal section along which an *x-z* slice of temperatures in the model after 30 hours is plotted in Figure 6b. We see a long wavelength mountain wave oscillation in the stratospheric temperatures. Visual inspection suggests a wavelength of ~300-400 km, consistent with the value inferred on 6th. November, 1994 by *Eckermann and Preusse* [1999].

Although these simulations are difficult to perform and generate large amounts of supercomputer data, the initial test simulations shown in Figure 6b provide very promising results. Thus, we will pursue further simulations and analysis of data in the coming quarter.

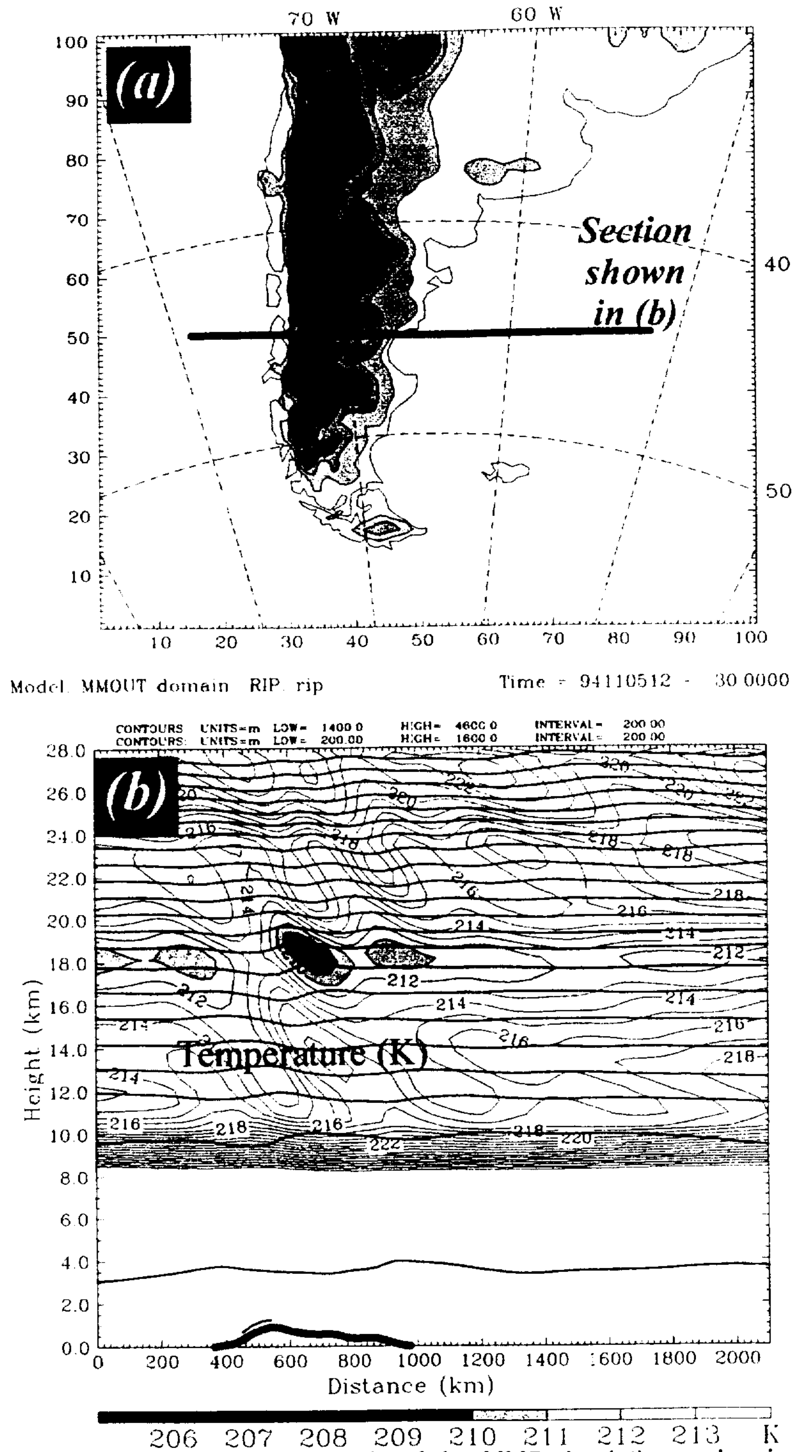

Figure 6: (a) Regional domain of the MM5 simulations, showing Andean topographic elevations used in MM5 and a red line showing the x-z section of temperatures plotted in (b); (b) Section of temperatures along red line in (a), 30 hours into the simulation. Contour labels and color bar numbers show temperatures in Kelvin. Andean topographic section is plotted with thick brown curve.

1.3 Self-Consistent Space-Time Synthesis of Mesospheric Temperature Data from HRDI and Ground-Based Instruments

In section 1.5 of the previous quarter's report, we reported on development of a model that we used to combine both UARS satellite data and ground-based data from the mesosphere optimally to order to get a better data-constrained estimate of the global atmospheric structure in this region (to aid gravity wave ray tracing experiments, for example). The approach was based on a space-time four-dimensional Fourier fitting model (using SVD methods). These results revealed some interesting features of the global mesospheric temperature field

To test and illustrate the method, we fitted mesospheric temperature data at 87 km and ~40°N from the HRDI instrument on UARS, and temperature data from two ground-based sensors: the Colorado State University (CSU) lidar and the Peach Mountain Interferometer. The different sampling characteristics of each instrument were illustrated last quarter. This quarter we have analyzed these globally synthesized temperature fields.

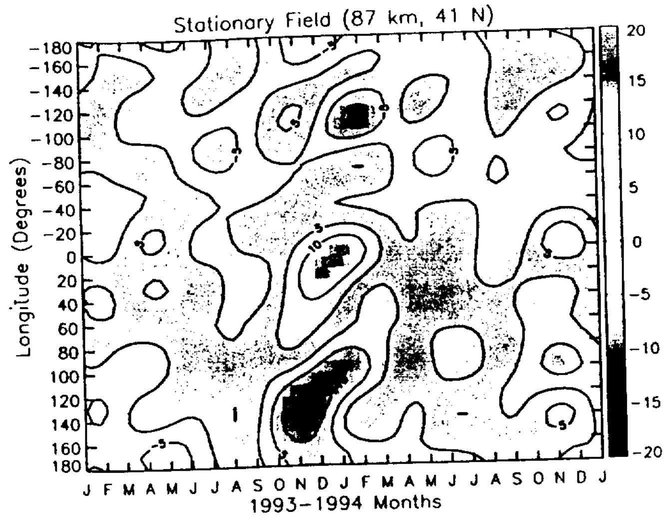

Figure 7: (a) Mid-latitude stationary temperature residuals at 87 km (day versus longitude), showing significant stationary planetary wave variations during winter months.

Figure 7 shows contours of temperature residuals at 87 km as a function of day number (months) and longitude for 1993 and 1994. The method shows clear evidence of stationary wavenumber 1-2 features in the temperature fields at these heights during late fall and winter, with amplitudes of up to 10-15 K. Similar features have been observed recently in mesospheric winds at these heights and latitudes during winter [e.g., *Smith*, 1997; *Wang et al.*, 2000] but have not been noted to date in temperatures to our knowledge. Based on this, we began drafting a paper on the method and these and other findings for submission to *Geophysical Research Letters* [*Drob et al.*, 2000].

2. Analysis

2.1 Interpretation of Results Obtained to Date

The research in this project has reached a highly sophisticated level of interpretation. In particular, we have developed and made extensive use of a two-dimensional nonlinear nonhydrostatic mesoscale model with a middle atmosphere capability to simulate stratospheric mountain waves over the southern Andes, as evident in data from CRISTA and MLS. Furthermore, we initiated a project this quarter to use a full three-dimensional mesoscale numerical prediction model (MM5) to model these waves during the CRISTA mission from first principles. Our results are yielding comparisons to a level of detail that was unprecedented at the beginning of this research project. The work shows that the southern Andes are a clear shource of long wavelength mountain waves for the stratosphere, that can be resolved by high-resolution limb-scanning satellites like MLS and CRISTA.

2.2 Recommended Further Action

Following on from the research in section 1 and the discussion in section 2.1, it is now clear that stratospheric mountain waves over the southern Andes are of sufficient amplitude and wavelength scales to be resolved by state-of-the-art limb scanning satellite instruments like MLS and CRISTA, as inferred in analyses of radiance and temperature data. A question we have now begun asking is whether other instruments on UARS should also have detected these waves during the UARS mission. One likely candidate appears to be CLAES, since it uses a (single telescope) limb-scanning procedure that is quite similar to CRISTA. Yet gravity waves have not been noted to date in these data. Thus, in the upcoming quarter we will acquire sample CLAES temperature data from the UARS/DAAC archive and see whether there is evidence of mountain waves in the CLAES temperature data over the southern Andes.

Our work next quarter will also focus further on the two-dimensional and three-dimensional mesoscale model simulations that have produced such encouraging results this quarter. With our writeup of the two-dimensional modeling work, which has been accepted for publication [*Tan and Eckermann*, 2000], we anticipate focusing more on the three-dimensional modeling work with MM5 outlined in section 1.2. We will also see the writeup of the work on combining HRDI and ground-based temperature data (section 1.3) through to final publication [*Drob et al.*, 2000].

2.3 Relation to Ultimate Objectives of the Research Contract

Given the mature mesoscale modeling work outlined in this project, it now can be truly said that we have a very good understanding of some specific sources of large-scale mountain waves in the middle atmosphere as observed by satellite instruments like CRISTA and MLS. It is useful to compare this to the situation at the start of this project. Just a few years earlier, it was still speculation whether radiance variances measured by MLS in the middle atmosphere gave fundamental gravity wave information, and it was unclear whether CRISTA data contained any information on gravity waves at all. Further, clear specific sources of gravity waves for the middle atmosphere were largely unknown – in particular, the role of the southern Andes in launching large amplitude long-wavelength mountain waves into the middle atmosphere was entirely unknown. The work to date has not only provided data on these waves, but now has provided extremely detailed and sophisticated numerical models of their form and evolution (see sections 1.1 and 1.2). This has fulfilled the goals of this research project in a depth that was entirely unanticipated (and probably thought unlikely or even impossible) at the start of this research project.

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